

## (12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization  
International Bureau



(43) International Publication Date  
21 February 2002 (21.02.2002)

PCT

(10) International Publication Number  
**WO 02/14906 A1**

- (51) International Patent Classification<sup>7</sup>: **G01V 3/12**
- (21) International Application Number: PCT/GB01/03473
- (22) International Filing Date: 2 August 2001 (02.08.2001)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:  
0019956.2 14 August 2000 (14.08.2000) GB  
0023921.1 29 September 2000 (29.09.2000) GB
- (71) Applicant: STATOIL ASA [NO/NO]; N-4035 Stavanger (NO).
- (71) Applicant (for IS only): REES, David, Christopher [GB/GB]; Kilburn & Strode, 20 Red Lion Street, London WC1R 4PJ (GB).
- (72) Inventors; and
- (75) Inventors/Applicants (for US only): ELLINGSRUD, Svein [NO/NO]; Tyholt alle 9A, N-7052 Trondheim (NO). EIDESMO, Terje [NO/NO]; Markapl. 5, N-7054 Ranheim (NO). PEDERSEN, Hans, Magne [NO/NO]; Hans Hagrups gate 8, N-7012 Trondheim (NO).
- (80) Designated States (national): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.
- (84) Designated States (regional): ARIPO patent (GII, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

## Published:

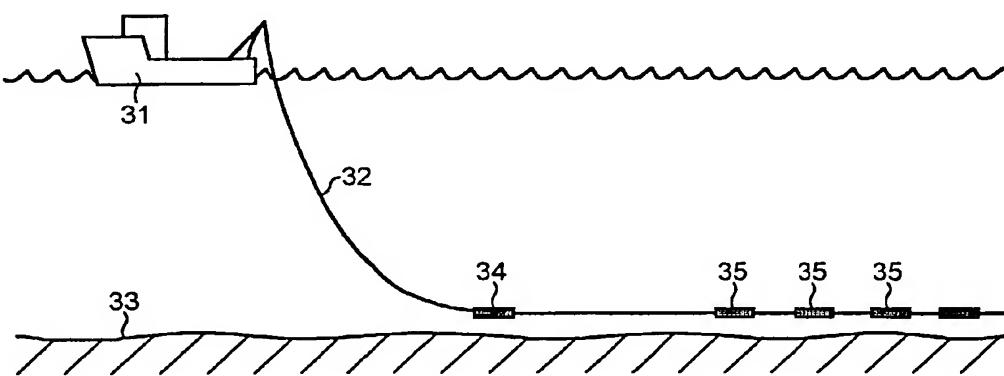
— with international search report

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: METHOD AND APPARATUS FOR DETERMINING THE NATURE OF SUBTERRANEAN RESERVOIRS



**WO 02/14906 A1**



(57) Abstract: A system for detecting or determining the nature of a subterranean reservoir. An electromagnetic field is applied using a dipole antenna transmitter and this is detected using a dipole antenna receiver. The measurements are taken with the antenna both in-line and parallel and the difference between the two sets of measurements is exploited. A characteristic difference indicates a high resistive layer, which corresponds to a hydrocarbon reservoir.

Method and Apparatus for Determining  
the Nature of Subterranean Reservoirs

- The present invention relates to a method and apparatus for determining the nature of submarine and subterranean reservoirs. The invention is particularly suitable for determining whether a reservoir, whose approximate geometry and location are known, contains hydrocarbons or water, though it can also be applied to detecting reservoirs with particular characteristics.
- Currently, the most widely used techniques for geological surveying, particularly in submarine situations, are seismic methods. These seismic techniques are capable of revealing the structure of the subterranean strata with some accuracy. However, whereas a seismic survey can reveal the location and shape of a potential reservoir, it cannot reveal the nature of the reservoir.
- The solution therefore is to drill a borehole into the reservoir. However, the costs involved in drilling an exploration well tend to be in the region of £25m and since the success rate is generally about 1 in 10, this tends to be a very costly exercise.
- It is therefore an object of the invention to provide a system for determining, with greater certainty, the nature of a subterranean reservoir without the need to sink a borehole.
- It has been appreciated by the present applicants that while the seismic properties of oil-filled strata and water-filled strata do not differ significantly, their electromagnetic resistivities (permittivities) do differ. Thus, by using an electromagnetic surveying method, these differences can be exploited and the success rate in predicting the nature of a reservoir can be increased significantly. This

represents potentially an enormous cost saving.

Consequently, a method and apparatus embodying these principles from the basis of the present applicant's co-pending International patent application PCT/GB01/00419.

5

This contemplates a method of determining the nature of a subterranean reservoir whose approximate geometry and location are known, which comprises: applying a time varying electromagnetic field to the strata containing the reservoir; detecting the electromagnetic wave field response; seeking in the wave field response, a component representing a refracted wave from the hydrocarbon layer; and determining the content of the reservoir, based on the presence or absence of a wave component refracted by the hydrocarbon layer.

It also contemplates a method for searching for a hydrocarbon containing subterranean reservoir which comprises: applying a time varying electromagnetic field to subterranean strata; detecting the electromagnetic wave field response; seeking, in the wave field response, a component representing a refracted wave; and determining the presence and/or nature of any reservoir identified based on the presence or absence of a wave component refracted by hydrocarbon layer.

15

It further contemplates an apparatus for determining the nature of a subterranean reservoir whose approximate geometry and location are known, or for searching for a hydrocarbon containing subterranean reservoir, the apparatus comprising: means for applying a time varying electromagnetic field to the strata containing the reservoir; means for detecting the electromagnetic wave field response; and means for seeking, in the wave field response, a component representing a refracted wave, thereby enabling the presence and/or nature of a reservoir to be determined.

A refracted wave behaves differently, depending on the nature of the stratum in which it is propagated. In particular, the propagation losses in hydrocarbon stratum are much lower than in a water-bearing stratum while the speed of propagation is much higher. Thus, when an oil-bearing reservoir is present, and an EM field is applied, a strong and rapidly propagated refracted wave can be detected. This may therefore indicate the presence of the reservoir or its nature if its presence is already known.

Electromagnetic surveying techniques in themselves are known. However, they are not widely used in practice. In general, the reservoirs of interest are about 1 km or more below the seabed. In order to carry out electromagnetic surveying as a stand alone technique in these conditions, with any reasonable degree of resolution, short wavelengths are necessary. Unfortunately, such short wavelengths suffer from very high attenuation. Long wavelengths do not provide adequate resolution. For these reasons, seismic techniques are preferred.

However, while longer wavelengths applied by electromagnetic techniques cannot provide sufficient information to provide an accurate indication of the boundaries of the various strata, if the geological structure is already known, they can be used to determine the nature of a particular identified formation, if the possibilities for the nature of that formation have significantly differing electromagnetic characteristics. The resolution is not particularly important and so longer wavelengths which do not suffer from excessive attenuation can be employed.

The resistivity of seawater is about 0.3 ohm-m and that of the overburden beneath the seabed would typically be from 0.3 to 4 ohm-m, for example about 2 ohm-m. However, the resistivity of an oil reservoir is likely to be about 20-300 ohm-m. This large difference can be exploited using the techniques of the present invention.

Typically, the resistivity of a hydrocarbon-bearing formation will be 20 to 300 times greater than water-bearing formation.

- 5 Due to the different electromagnetic properties of a gas/oil bearing formation and a water bearing formation, one can expect a reflection and refraction of the transmitted field at the boundary of a gas/oil bearing formation. However, the similarity between the properties of the overburden and a reservoir containing water means that no reflection or refraction is likely to occur.
- 10 Thus, an electric dipole transmitter antenna on or close to the sea floor induces electromagnetic (EM) fields and currents in the sea water and in the subsurface strata. In the sea water, the EM-fields are strongly attenuated due to the high conductivity in the saline environment, whereas the subsurface strata with less conductivity potentially can act as a guide for the EM-fields (less attenuation). If the frequency is low enough (in the order of 1 Hz), the EM-waves are able to penetrate deep into the subsurface, and deeply buried geological layers having higher electrical resistivity than the overburden (as e.g. a hydrocarbon filled reservoir) will affect the EM-waves. Depending on the angle of incidence and state of polarisation, an EM wave incident upon a high resistive layer may excite a ducted (guided) wave mode in the layer. The ducted mode is propagated laterally along the layer and leaks energy back to the overburden and receivers positioned on the sea floor. The term "refracted" wave in this specification is intended to refer to this wave mode.
- 15
- 20
- 25 Both theory and laboratory experiments show that the ducted mode is excited only for an incident wave with transverse magnetic (TM) polarisation (magnetic field perpendicular to the plane of incidence) and at angles of incidence close to the Brewster angle and the critical angle (the angle of total reflection). For transverse electric (TE) polarisation (electric field perpendicular to the plane of incidence) the

ducted mode will not be excited. Since the induced current is proportional to the electric field, the current will be parallel to the layer interfaces for TE polarisation but, for TM polarisation, there is an appreciable current across the layer interfaces.

- 5      A horizontal dipole source on the sea floor will generate both TE and TM waves, but by varying the orientation of the receiver antennae, it is possible to vary the sensitivity to the two modes of polarisation. It appears that an in-line orientation (source and receiver dipoles in-line) is more sensitive to the TM mode of polarisation, whereas a parallel orientation (source and receiver dipoles in parallel) is  
10     more sensitive to the TM mode of polarisation. The TM mode is influenced by the presence of buried high resistive layers, whereas the TE mode is not. By measuring with the two antenna configurations and exploiting the difference between the two sets of measurements, it is possible to identify deeply buried high resistivity zones, i.e. a hydrocarbon reservoir.

15

The present invention has arisen from this realisation.

- According to one aspect of the present invention, there is provided, a method of determining the nature of a subterranean reservoir which comprises: deploying an  
20     electric dipole transmitter antenna with its axis generally horizontal; deploying an electric dipole receiver antenna in-line with the transmitter; applying an electromagnetic (EM) field to the strata containing the reservoir using the transmitter; detecting the EM wave field response using the receiver and identifying in the response a component representing a refracted wave from the reservoir according to a first mode; deploying an electric dipole receiver antenna parallel to the transmitter; applying an EM field to the strata using the transmitter; detecting the EM wave field response using the receiver and identifying in the response a component representing a refracted wave from the reservoir according to a second

mode; and comparing the first mode refractive wave response with the second mode refracted wave response in order to determine the nature of the reservoir.

According to another aspect of the present invention there is provided, a method of  
5 searching for a hydrocarbon-containing subterranean reservoir which comprises:  
deploying an electric dipole transmitter antenna with its axis generally horizontal;  
deploying an electric dipole receiver antenna in-line with the transmitter; applying an  
EM field to subterranean strata using the transmitter; detecting the EM wave field  
response using the receiver; seeking in the response a component representing a  
10 refracted wave according to a first mode, caused by a high-resistivity zone;  
deploying an electric dipole receiver antenna parallel to the transmitter; applying an  
EM field to the strata using the transmitter; detecting the EM wave field response  
using the receiver; seeking in the response a component representing a refracted  
wave according to a second mode; and comparing the first mode refractive wave  
15 response with the second mode refractive wave response in order to determine the  
presence and/or nature of any high-resistivity zone.

The first mode may be considered to be a TM mode, and the second mode a TE mode.

20 Thus, according to the invention, measurements are taken with the transmitter and receiver both in-line and parallel, and the two sets of measurements are compared.  
A characteristic difference in values indicates a highly resistive layer located beneath  
highly conductive strata. High resistivity indicates the presence of hydrocarbons and  
25 so the difference in values is a direct hydrocarbon indicator.

This technique can be used in conjunction with conventional seismic techniques to identify hydrocarbon reservoirs.

Preferably, the transmitter and/or receiver comprises an array of dipole antennae.

The technique is applicable in exploring land-based subterranean reservoirs but is  
5 especially applicable to submarine, in particular sub-sea, subterranean reservoirs.  
Preferably the field is applied using one or more transmitters located on the earth's  
surface, and the detection is carried out by one or more receivers located on the  
earth's surface. In a preferred application, the transmitter(s) and/or receivers are  
located on or close to the seabed or the bed of some other area of water.

10 In a preferred arrangement, the transmitter and receiver antennae are located on a  
common cable towed behind a vessel. This will result in a fixed offset or a series of  
fixed offsets where several receivers are employed. Preferably, the transmitter  
transmits both modes and may therefore comprise two dipoles arranged mutually at  
15 right angles. Preferably each receiver comprises two dipoles mutually at right  
angles. Preferably one transmitter dipole and one receiver dipole are arranged at  
right angles to the direction of the cable. Alternatively the transmitter and/or  
receivers may each comprise a single dipole antenna arranged obliquely, eg. at 45°  
to the direction of the cable. With this arrangement the transmitted field is resolved.

20 Using this technique, it is possible to achieve comparable results from the two modes  
as the same signal and offset are used. It will not matter greatly if the transmitter  
drifts in frequency or amplitude. Furthermore, reservoirs can be detected in real  
time. Thus, if the results show a difference in the two modes, this will strongly  
25 indicate the presence of an H/C bearing reservoir and so a more detailed study can  
be made at once.

Such a system would generally use a single transmission source and several

receivers, typically more than ten. The different offsets would be suitable for detecting reservoirs at different depths.

The receivers can be deployed on a single cable or on a series of parallel cables.

- 5 There may also be several transmitters.

In practice, the vessel would normally stop and the cable allowed to sink prior to transmission. There would be a transmission at several different frequencies before moving to another location. The technique is particularly suitable for edge detection, 10 and it is a simple matter to select a suitable resolution. However, if the surveying is being carried out in an undetermined area, the resistivity in the top layers should be mapped, for example with MT methods or by inversion after a reflection study.

If the offset between the transmitter and receiver is significantly greater than three 15 times the depth of the reservoir from the seabed (i.e. the thickness of the overburden), it will be appreciated that the attenuation of the refracted wave will often be less than that of direct wave and the reflected wave. The reason for this is the fact that the path of the refracted wave will be effectively distance from the transmitter down to the reservoir i.e. the thickness of the overburden, plus the offset 20 along the reservoir, plus the distance from the reservoir up to the receivers i.e. once again the thickness of the overburden.

The polarization of the source transmission will determine how much energy is transmitted into the oil-bearing layer in the direction of the receiver. A dipole 25 antenna is therefore the selected transmitter. In general, it is preferable to adopt a dipole with a large effective length. The transmitter dipole may therefore be 100 to 1000 meters in length and may be towed in two orthogonal directions. The receiver dipole optimum length is determined by the thickness of the overburden.

The transmitted field may be pulsed, however, a coherent continuous wave with stepped frequencies is preferred. It may be transmitted for a significant period of time, during which the transmitter should preferably be stationary (although it could 5 be moving slowly), and the transmission stable. Thus, the field may be transmitted for a period of time from 3 seconds to 60 minutes, preferably from 3 to 30 minutes, for example about 20 minutes. The receivers may also be arranged to detect a direct wave and a wave refracted from the reservoir, and the analysis may include extracting phase and amplitude data of the refracted wave from corresponding data 10 from the direct wave.

Preferably, the wavelength of the transmission should be in the range

$$0.1s \leq \lambda \leq 5s;$$

15

where  $\lambda$  is the wavelength of the transmission through the overburden and  $s$  is the distance from the seabed to the reservoir. More preferably  $\lambda$  is from about 0.5s to 2s. The transmission frequency may be from 0.01 Hz to 1 kHz, preferably from 1 to 20 Hz, for example 5 Hz.

20

Preferably, the distance between the transmitter and a receiver should be in the range

$$0.5 \lambda \leq L \leq 10 \lambda;$$

25

where  $\lambda$  is the wavelength of the transmission through the overburden and  $L$  is the distance between the transmitter and the first receiver.

It will be appreciated that the present invention may be used to determine the position,

the extent, the nature and the volume of a particular stratum, and may also be used to detect changes in these parameters over a period of time.

The present invention also extends to a method of surveying subterranean measures  
5 which comprises; performing a seismic survey to determine the geological structure of a region; and where that survey reveals the presence of a subterranean reservoir, subsequently performing a method as described above.

10 The invention may be carried into practice in various ways and will now be illustrated in the following embodiments and reduced scale investigations and simulations. In the accompanying drawings,

- Figure 1 is a vertical cross-section through a testing tank;
- 15 Figure 2 is a plan view of the tank of Figure 1;

- Figure 3 is a plan view of the antennae used in the tank of Figure 1;
- 20 Figure 4 is a side view of the antenna in Figure 3;
- Figures 5 and 6 are respectively a schematic plan view and side view of the testing tank set up for measurement;
- 25 Figures 7 is a graph showing calculated and measured values for the transmitted electric field for a given frequency in the model experiment;
- Figure 8 is a graph showing calculated values for the electric field in a realistic earth model;
- 30 Figure 9 is a schematic side view of a cable layout towed by a vessel;

Figure 10 is a plan view corresponding to Figure 9; and

5 Figures 11 and 12 are views similar to Figure 10 showing two alternative arrangements.

The tank 11 shown in Figure 1 and 2 comprises a concrete enclosure 9m long, 6m wide and 8m in depth. The tank 11 is filled with sea water 12. A diaphragm 13 filled  
10 with fresh water 14 is located in the tank. The diaphragm 13 is 7.5m long, 4.25m wide and 0.25m thick and can be located at any desired height in a horizontal orientation within the tank 11.

The conductivity of the sea water 12 was measured to be 5.3 S/m at 14°C and the conductivity of the fresh water was measured to be 0.013 S/m. The ratio of the two  
15 conductivities is therefore very close to 400.

The critical frequency  $f_c$  of a conducting medium, i.e. the frequency at which the displacement current is equal to the conduction current, is given by

$$20 \quad f_c = \frac{\sigma}{2\pi\epsilon_r\epsilon_0} \approx 18 \cdot \frac{\sigma}{\epsilon_r} \text{ GHz}$$

where  $\epsilon_r$  is the relative dielectric constant of the medium, and  $\sigma$  the conductivity in S/m. For water,  $\epsilon_r = 80$  at the frequencies and temperatures of interest. For the two  
25 conductivity values  $\sigma = 5.2$  S/m and  $\sigma = 0.013$  S/m,  $f_c = 1.2$  GHz and 3 MHz, respectively. Since, in the experiments, the highest frequency is 0.83 MHz, it is a fair approximation to neglect the displacement current, even for the fresh water.

For a non magnetic, conductive medium, the propagation constant  $\gamma$  is given by

$$\gamma = j\omega \sqrt{\epsilon\mu} = j\omega \sqrt{\left(\epsilon_r \epsilon_0 + \frac{\sigma}{j\omega}\right) \mu_0}$$

$$\approx \sqrt{j\omega \mu_0 \sigma} = 2\pi \sqrt{\frac{j \cdot f \sigma}{5}}$$

5

The wavelength  $\lambda$ , defined as the distance in which the phase changes  $2\pi$ , is given by

$$\lambda = \frac{2\pi}{\text{Re}\{\gamma\}} \approx \sqrt{\frac{10}{f\sigma}}$$

10

$\lambda$  m,  $f$  in MHz and  $\sigma$  in S/m. The skin depth, the distance in which the amplitude diminishes by  $1/e$ , is related to the wavelength by

$$\delta = \frac{\lambda}{2\pi} = \sqrt{\frac{\pi}{2f\mu_0\sigma}}$$

15

For the extremes of the frequency range, for the sea water with  $\sigma = 5.2$  S/m,

	Frequency	30 kHz	830 kHz
	Skin depth	1.27 m	0.24 m
20	Wavelength	8.01 m	1.52 m

and for the fresh water with  $\sigma = 0.013$  S/m,

	Frequency	30 kHz	830 kHz
25	Skin depth	25.4 m	4.8 m
	Wavelength	160.2 m	30.4 m

Referring now to Figures 3 and 4, two identical electrical dipole antennae, as shown were used for the transmitter and receiver.

5        Each antenna 15 comprises two square brass plates 16, 15cm square, mounted on an epoxy substrate 17. Each plate 16 is connected to a co-axial cable 18, which passes through an epoxy tube 19 mounted at right angles to the plate 16, to a balun which transforms the impedance of the antenna 15 from about  $2\Omega$  in sea water to about  $50\Omega$ .

10      The measurement set-up is shown in Figure 5 and 6. An automatic network analyser (ANA) measures the transmission between the antennae 15 as a function of distance (offset) and frequency. The arrangement shown in Figure 5 shows the antennae 15 in the parallel orientation. The in-line orientation is achieved by rotating both antennae through  $90^\circ$  in the horizontal plane.

15      The results of the measurements are shown in Figure 7 together with the corresponding theoretical results. The measurements agree well with the theoretical results and the figure contains two sets of curves, one with parallel antennae and one with the antennae in line. The theoretical results are computed for infinitesimal dipole antennae. The orientations of the antennae and the frequency are shown on the  
20      Figures.

The parameters of the experiment are scaled relative to possible practical situations. To give an idea of orders of magnitude; if the frequency is scaled down by a factor of 40,000 and the conductivity by a factor of 10, the dimensions will be scaled up by a  
25      factor of 632, and the experimental setup would correspond to a low conductivity layer of thickness 150 m and conductivity 0.0013 S/m below an overburden of thickness 300 m and conductivity 0.52 S/m. The corresponding frequency range would be from 0.75 Hz to 20 Hz, and the length of the antenna nearly 300 m.

30      The method with the TE and TM-mode have been tested by computer simulations on a

simple horizontally-layered earth model with electrical parameter values for typical deep water subsurface sediments. The model has an infinite insulating air layer, a 1150 meter water layer of  $0.3125\Omega m$ , 950 meter overburden of  $1\Omega m$ , a 150 meter reservoir zone of  $50\Omega m$  and an infinite underburden of  $1\Omega m$ . Figure 8 illustrates the 5 amplitude response  $|E|$  (electric field) as a function of receiver offset, caused by a 1 Hz signal. Responses from both the TM-mode (solid with x's) and TE-mode (dashed with +'s) are shown. The amplitudes for the TM-mode are approximately 10 times larger at an offset of 5 km. As a reference, the response from a homogenous half-space of  $1\Omega m$  is shown for both configurations (corresponding to a response from a 10 water filler reservoir or outside the reservoir area). The TE-mode has the largest deviation from its half-space, ie. this mode is more sensitive to a hydrocarbon layer.

Figures 9 and 10 show a vessel 31 towing a cable (or streamer) 32 just above the seabed 33. The cable 32 carries a transmitter dipole antenna 34 and several receiver 15 dipoles 35, only four of which are shown. The depth of water might be of the order of 1000m, the offset between the transmitter 34 and the nearest receiver 35 might be about 2000m and the receivers might be about 100m apart. The transmitter 34 is controlled from the vessel 31 via the cable 32 and the responses detected by the 20 receivers 35 are relayed back to the vessel 31 in real time, again via the cable 32.

Figure 10 shows an arrangement in which the vessel 31 tows three cables 41, 42, 43, each carrying a series of receivers 45, 46, 47. The spacing of the three cables 41, 42, 43 is achieved by means of a spar 44.

25 In the arrangement shown in Figure 11, the transmitter 48 is in the form of two dipole antennae, one parallel to the cable 42 and one at right angles.

The arrangement shown in Figure 12 is similar to Figure 11, but in this case, the transmitter 51 is a single dipole antenna arranged at  $45^\circ$  to the cable 42.

Claims

1. A method of determining the nature of a subterranean reservoir which comprises: deploying an electric dipole transmitter antenna with its axis generally horizontal; deploying an electric dipole receiver antenna in-line with the transmitter; applying an electromagnetic (EM) field to the strata containing the reservoir using the transmitter; detecting the EM wave field response using the receiver and identifying in the response a component representing a refracted wave from the reservoir according to a first mode; deploying an electric dipole receiver antenna parallel to the transmitter; applying an EM field to the strata using the transmitter; detecting the EM wave field response using the receiver and identifying in the response a component representing a refracted wave from the reservoir according to a second mode; and comparing the first mode refractive wave response with the second mode refracted wave response in order to determine the nature of the reservoir.
2. A method of searching for a hydrocarbon-containing subterranean reservoir which comprises: deploying an electric dipole transmitter antenna with its axis generally horizontal; deploying an electric dipole receiver antenna in-line with the transmitter; applying an EM field to subterranean strata using the transmitter; detecting the EM wave field response using the receiver; seeking in the response a component representing a refracted wave according to a first mode, caused by a high-resistivity zone; deploying an electric dipole receiver antenna parallel to the transmitter; applying an EM field to the strata using the transmitter; detecting the EM wave field response using the receiver; seeking in the response a component representing a refracted wave according to a second mode; and comparing the first mode refractive wave response with the second mode refractive wave response in order to determine the presence and/or nature of any high-resistivity zone.

3. A method as claimed in Claim 1 or Claim 2, characterised in that the first mode is a TM mode of polarisation and/or the second mode is a TE mode of polarisation.

5

4. A method as claimed in any preceding Claim, characterised in that the transmitter and/or receiver comprises an array of dipole antennae.

10

5. A method as claimed in any preceding Claim, characterised in that the transmitter and/or receiver is located on or close to the seabed or the bed of some other area of water.

15

6. A method as claimed in any preceding Claim, characterised in that the transmitter and receivers are located on a common cable arranged to be towed behind a vessel.

7. A method as claimed in any preceding Claim, characterised in that the transmitter comprises two dipole antennae arranged mutually at right angles.

20

8. A method as claimed in any preceding Claim, characterised in that each receiver comprises two dipole antennae arranged mutually at right angles.

25

9. A method as claimed in Claim 6 characterised in that the transmitter and/or receiver each comprise a single dipole antenna arranged obliquely to the direction of the cable.

10. A method as claimed in any preceding Claim, characterised in that the frequency of the EM field is continuously varied over the transmission period.

11. A method as claimed in any preceding Claim, characterised in that the field is transmitted for a period of time for 3 seconds to 60 minutes.

5 12. A method as claimed in Claim 11, characterised in that the transmission time is from 3 to 30 minutes.

13. A method as claimed in any preceding Claim, characterised in that the wavelength of the transmission is given by the formula

10

$$0.1s \leq \lambda \leq 10s;$$

wherein  $\lambda$  is the wavelength of the transmission through the overburden and s is the distance from the seabed to the reservoir.

15

14. A method as claimed in any preceding Claim, characterised in that distance between the transmitter and a receiver is given by the formula

20

$$0.5 \leq \lambda \leq 10s;$$

where  $\lambda$  is the wavelength of the transmission through the overburden and 1 is the distance between the transmitter and the receiver.

25

15. A method as claimed in any of Claims 10 to 14, characterised in that the transmission frequency is from 0.01 Hz to 1 kHz.

16. A method as claimed in Claim 15, characterised in that the transmission frequency is from 1 to 20 Hz.

17. A method as claimed in any preceding Claim, characterised in that it includes suppressing the direct wave and/or any other known wave contribution that may disturb the measurements, thereby reducing the required dynamic range of the receiver and increasing the resolution of the refracted wave.

5

18. A method of surveying subterranean measures which comprises: performing a seismic survey to determine the geological structure of a region and where that survey reveals the presence of a subterranean reservoir, subsequently performing a method as claimed in any preceding Claim.

1 / 6

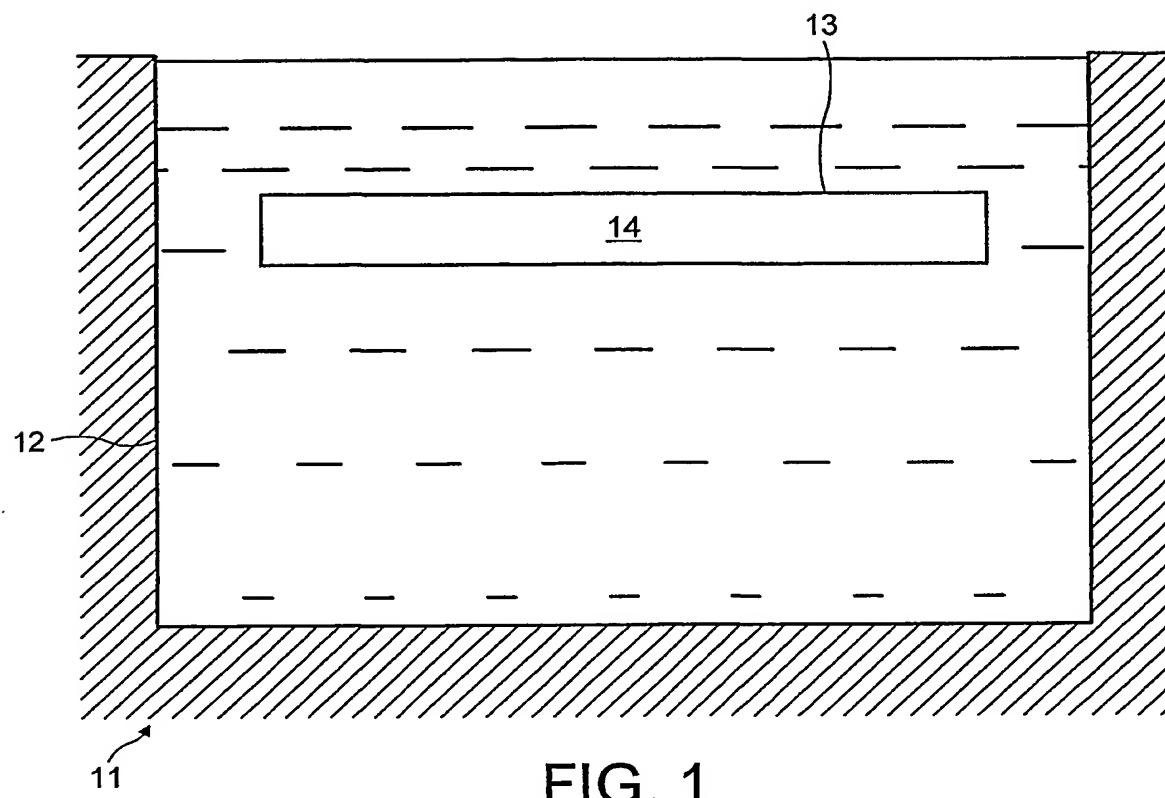


FIG. 1

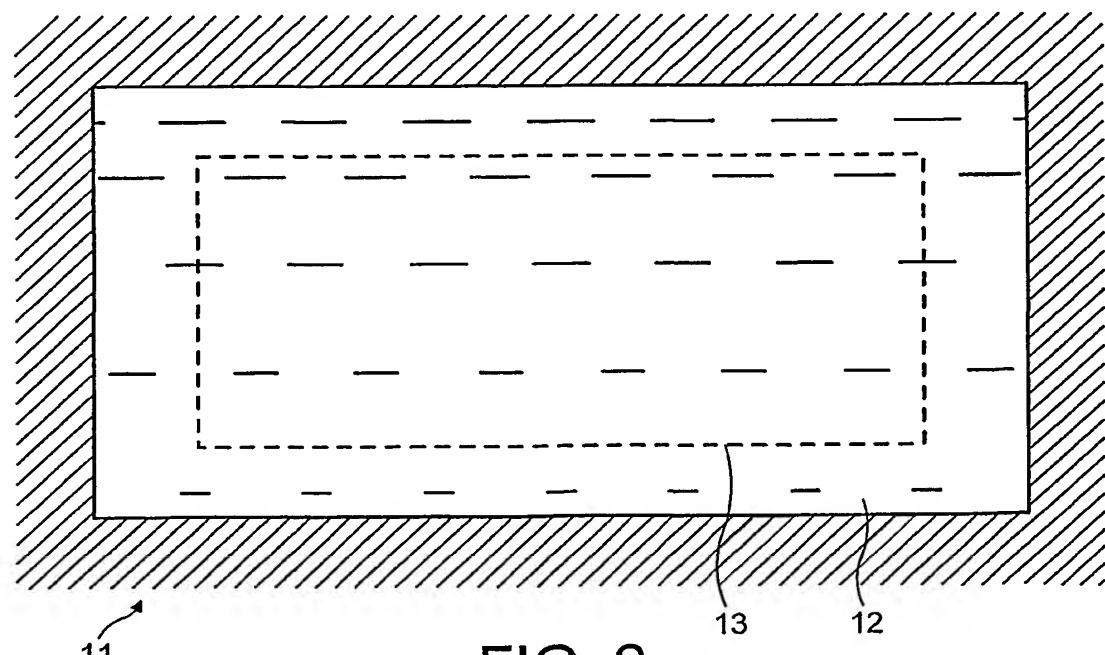


FIG. 2

2 / 6

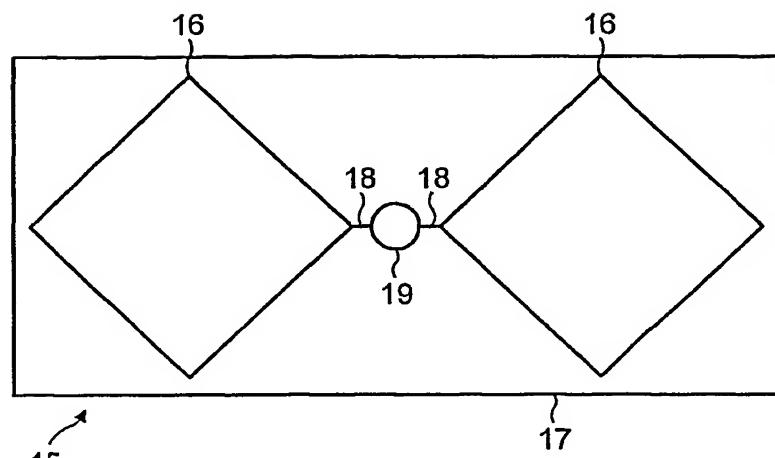


FIG. 3

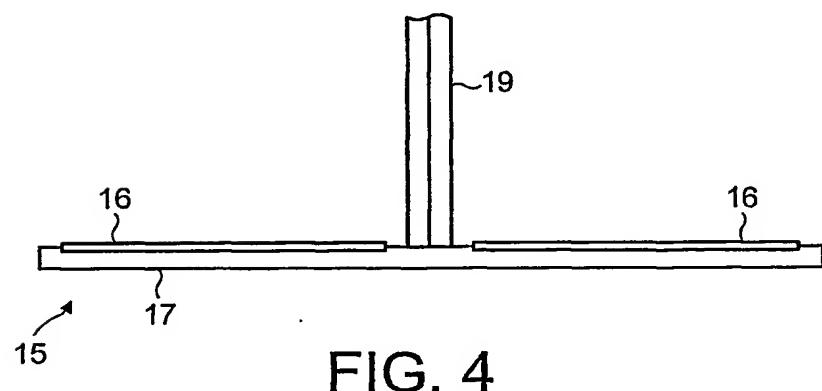
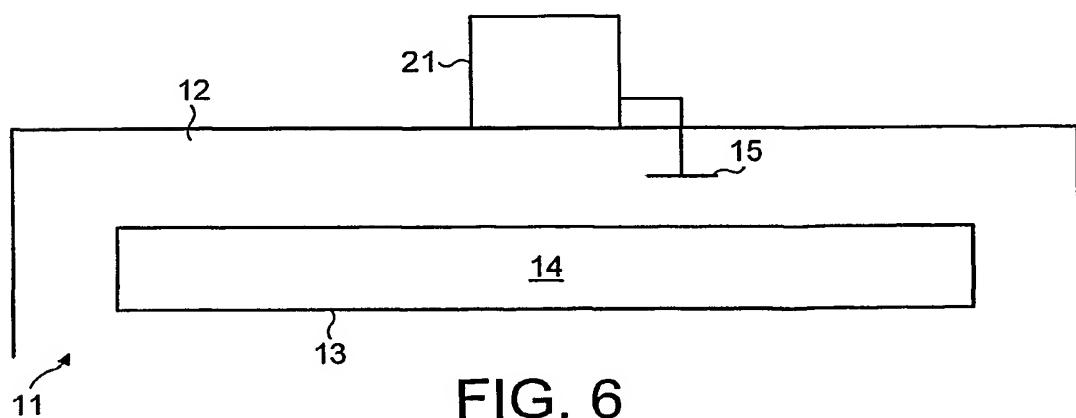
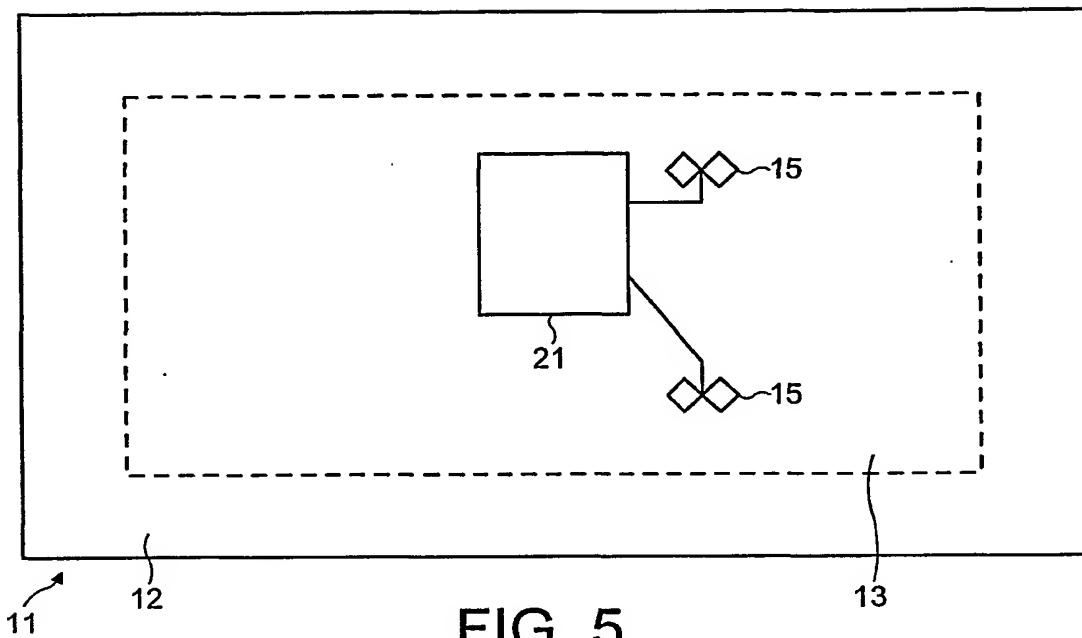


FIG. 4

3 / 6



4 / 6

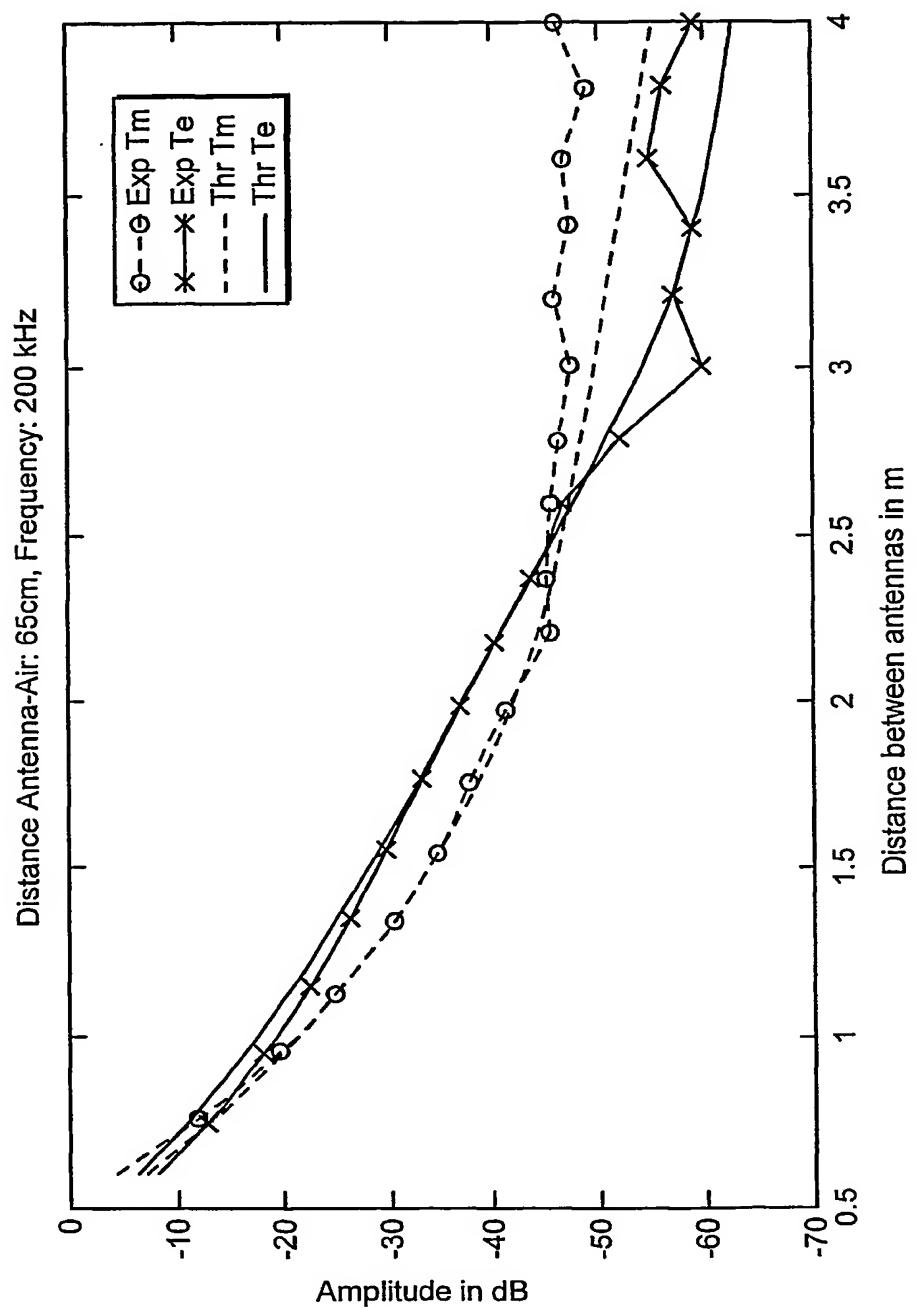


FIG. 7

5 / 6

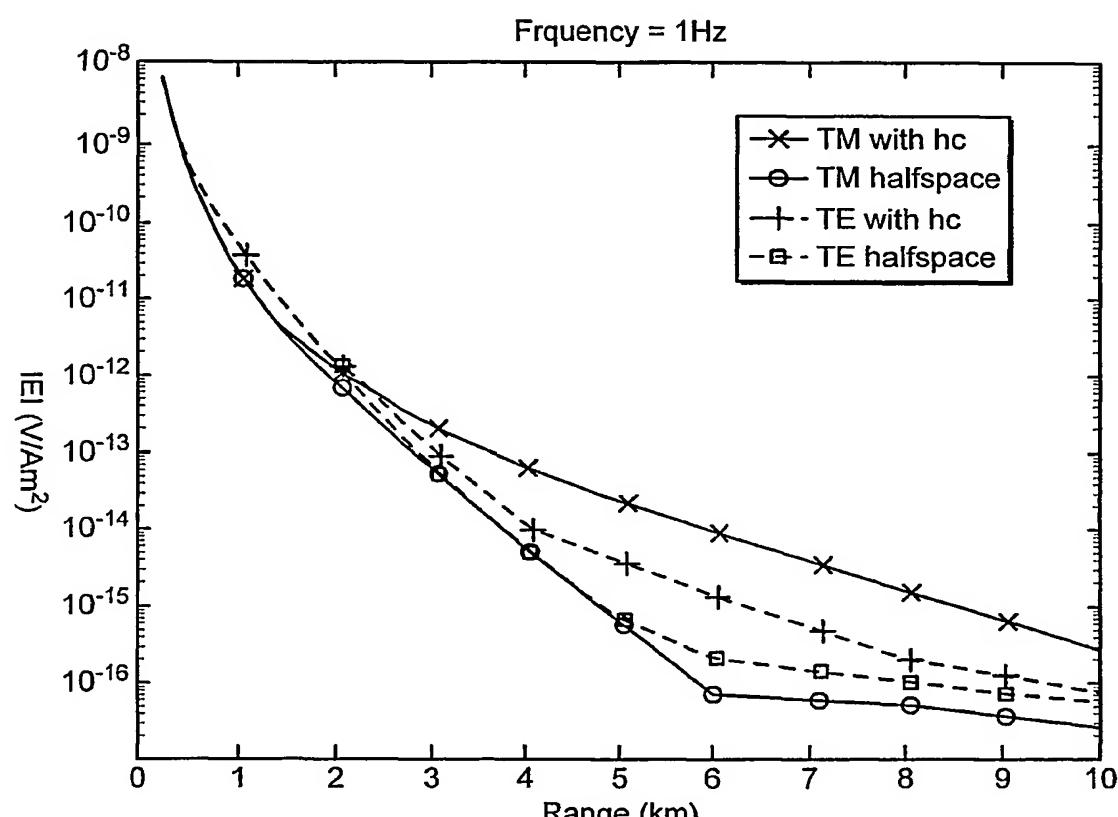


FIG. 8

6 / 6

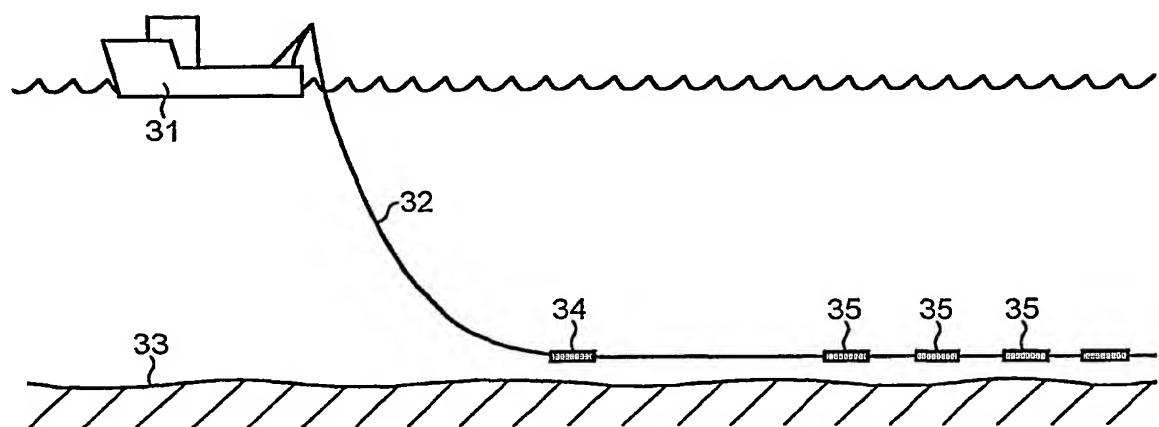


FIG. 9

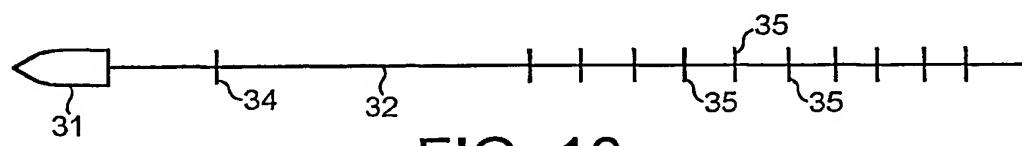


FIG. 10

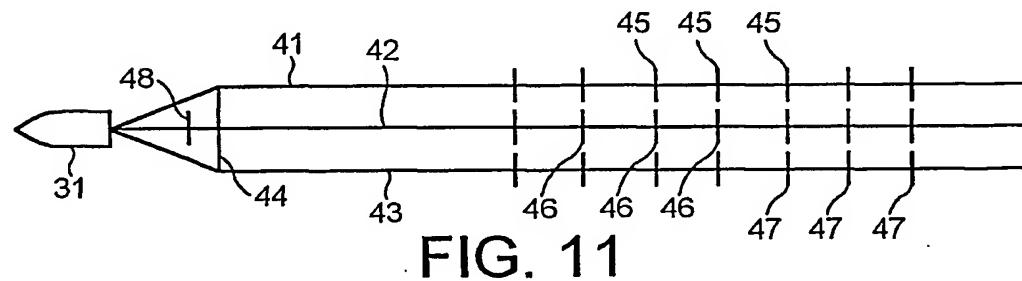


FIG. 11

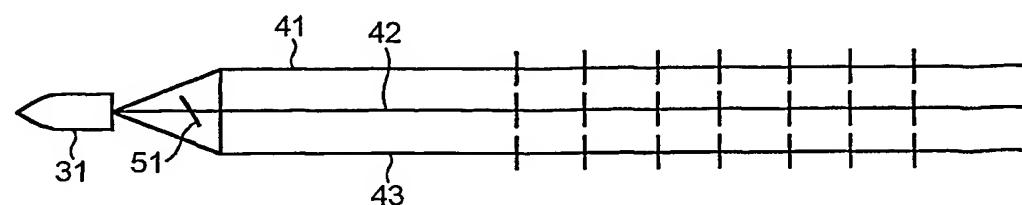


FIG. 12

## INTERNATIONAL SEARCH REPORT

Inte al Application No

PCT/GB 01/03473

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 7 G01V3/12

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
IPC 7 G01V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the International search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC, COMPENDEX

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4 617 518 A (SRNKA LEONARD J) 14 October 1986 (1986-10-14) abstract; figures 1,2 ---	1,2
A	US 2 077 707 A (STARR MELTON BENJAMIN) 20 April 1937 (1937-04-20) the whole document page 1, left-hand column, line 32 - line 39; claim 1 ---	1,2
A	US 4 258 321 A (NEALE JR DORY J) 24 March 1981 (1981-03-24) abstract; figures 6-8 column 2, line 29 - line 47 column 3, line 62 -column 4, line 2 ---	1,2 -/-

 Further documents are listed in the continuation of box C. Patent family members are listed in annex.

## \* Special categories of cited documents:

- \*A\* document defining the general state of the art which is not considered to be of particular relevance
- \*E\* earlier document but published on or after the International filing date
- \*L\* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- \*O\* document referring to an oral disclosure, use, exhibition or other means
- \*P\* document published prior to the International filing date but later than the priority date claimed

\*T\* later document published after the International filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

\*X\* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

\*Y\* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

\*&\* document member of the same patent family

Date of the actual completion of the International search

22 October 2001

Date of mailing of the international search report

26/10/2001

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,  
Fax (+31-70) 340-3016

Authorized officer

De Bekker, R

## INTERNATIONAL SEARCH REPORT

Inte  
al Application No  
PCT/GB 01/03473

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4 047 098 A (DUROUX JEAN) 6 September 1977 (1977-09-06) the whole document ----	1,2
P,A	WO 00 54075 A (KUO JOHN T ;PROFILE TECHNOLOGIES INC (US)) 14 September 2000 (2000-09-14) abstract; claim 1; figure 5 page 16, line 9 -page 17, line 13 ----	1-18
A	US 5 400 030 A (DUREN RICHARD E ET AL) 21 March 1995 (1995-03-21) abstract; figures 1,4 ----	1,2
T	WO 01 57555 A (REES DAVID CHRISTOPHER ;NORGES GEOTEKNISKE INST (NO); WESTERDAHL H) 9 August 2001 (2001-08-09) cited in the application the whole document ----	1-18

## INTERNATIONAL SEARCH REPORT

Int'l Application No
PCT/GB 01/03473

Patent document cited in search report	Publication date		Patent family member(s)		Publication date
US 4617518	A 14-10-1986	AU ES ES FR GB JP NL NO	3571784 A 537787 D0 8606671 A1 2555322 A1 2155182 A 60135783 A 8403541 A 844614 A		30-05-1985 01-04-1986 01-10-1986 24-05-1985 18-09-1985 19-07-1985 17-06-1985 22-05-1985
US 2077707	A 20-04-1937		NONE		
US 4258321	A 24-03-1981		NONE		
US 4047098	A 06-09-1977	FR	2288988 A1		21-05-1976
WO 0054075	A 14-09-2000	AU WO	3622200 A 0054075 A1		28-09-2000 14-09-2000
US 5400030	A 21-03-1995	CA DE FR	2118140 A1 4435792 A1 2716006 A1		10-08-1995 10-08-1995 11-08-1995
WO 0157555	A 09-08-2001	WO	0157555 A1		09-08-2001